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THE EFFECTS OF FIRE ON ROCK WEATHERING: SOME FURTHER CONSIDERATIONS OF LABORATORY EXPERIMENTAL SIMULATION

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ABSTRACT

Fire in the natural environment is a widespread agent of geomorphological and biological change. Temperatures can exceed 1000°C. There is often a rapid rise from ambient conditions through a steep thermal gradient, promoting rock disintegration. Laboratory simulation studies have established that temperature changes which are representative of natural fires affect rock material properties, which can then be related to weathering susceptibility. This study extends previous work by more closely replicating the natural environment, (a) through the simulation of rainfall and (b) by encasing samples to reflect the exposure of a single rock face to a passing fire event. Rock samples collected on Cyprus were prepared and tested following previously reported procedures. Change in modulus of elasticity was monitored using a non-destructive ultrasonic method. The data corroborate previous work but with somewhat different degrees of change. The new results are more likely to be representative of natural conditions and real-world change. The rate of rock disintegration and effects such as case-hardening appear to be a function of rock thermal characteristics, material properties and environmental constraints such as diurnal temperature range. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: rock weathering; fire; geotechnics; Dynamic Young's Modulus

INTRODUCTION

While it is undisputed that fire is a significant agent of change in the natural environment (Ollier and Ash, 1983), there is little work which quantifies the effects of fire as a geomorphological agent. Two studies which use laboratory simulation to measure the effects of fire on rock weathering are reported by Goudie *et al.* (1992) and Allison and Goudie (1994). They use a furnace to heat rock samples and establish changes to Dynamic Young's Modulus, using non-destructive ultrasonic methods (Allison, 1987, 1988, 1989). Modulus of elasticity provides an indication of rock susceptibility to weathering and disintegration. This study is based on the previous methods but with two adaptations to procedure, designed to give results which are more likely to reflect real-world conditions. First, samples were encased in fine sand, leaving one rock face exposed prior to firing. This will affect heat transfer into the rock and be more realistic of the natural environment than just placing samples on a flat surface within the furnace. Second, some of the samples were sprayed with water upon removal from the furnace. This part of the experiment was designed to reflect the fact that many natural fires are followed by precipitation events. Vegetation ignites, temperatures rise rapidly over a short period of time, peak temperatures may be reached in less than 2 min (Adamson *et al.*, 1983). Rainfall from fire-generated atmospheric convection may follow soon after the conflagration (Pyne, 1982, 1991; Booysen and Tainton, 1984; Goldammer, 1990). Data were compared with results from previous studies and variations used to establish the effects of the new test procedures since the experimental conditions approach more closely those encountered by stone in nature.

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METHODS

A range of rock types were collected from the island of Cyprus, an environment in which fire occasionally sweeps across the landscape. All samples were of unweathered material and collected from *in situ* outcrops. Six different materials were used in the study, some for their similarity with rocks used in previous laboratory simulations and others because of their contrasting mineralogy: Dolerite – medium quartz, feldspar rich, basic, medium grain; Wehrlite – clino-pyroxene/olivine rich, high density, ultra-basic, medium grain; Gabbro – clino-pyroxene/plagioclase rich, medium quartz, intermediate density; Chalk – silica rich, medium porosity; Serpentinite – ortho-pyroxene/olivine rich, low quartz, poikiolitic grains; Dolerite – medium quartz, low density.

Laboratory procedure followed previous methodology (Goudie *et al.*, 1992; Allison and Goudie, 1994) to eliminate between-test variability and permit the comparison of results. Test specimens were cut into bars measuring 15 cm by 3 cm by 2 cm using a diamond-bladed saw and flat-bed grinder. The cut blocks were dried to constant weight at 50°C and 20 per cent relative humidity in an environmental chamber. The dry weight of each block was recorded and modulus of elasticity determined using the Grindosonic apparatus, a non-destructive, ultrasonic technique. Modulus of elasticity is a good indicator of rock competence (Judd and Huber, 1962; D'Andrea *et al.*, 1965; Deere and Miller, 1966) and provides an indication of resistance to weathering and erosion (e.g Attewell and Farmer, 1976; Dearman *et al.*, 1978; Cooks, 1983) relative to parameters such as mineralogy, texture, density, porosity, water content, the nature and composition of any cementing material, and anisotropy (Richter and Simmons, 1974). Three different sorts of test were undertaken.

1. Blocks were placed in a furnace for 5 min at 500°C, to represent temperatures recorded in a number of natural fires (Goudie *et al.*, 1992). After 5 min in the furnace, samples were returned to the environmental chamber, left to return to ambient conditions, weighed and their modulus of elasticity measured. The procedure was repeated seven times. This part of the test programme was identical to previous work and is therefore the control against which other results can be compared.
2. The above procedure was repeated but immediately upon removal from the furnace each sample was sprayed with 10 ml of water, to simulate a precipitation event. This differs from Allison and Goudie (1994), where test specimens were saturated before being placed in the furnace. Water was applied after each heating cycle. The water will alter the rock cooling rate, generate additional stresses relative to the thermal heat capacity and material conductivity, and affect rock competence as reflected in the elastic properties.
3. For the third suite of tests, samples were embedded in fine sand prior to placing them in the furnace, exposing a single face to direct heating. Exposing one side of a sample reflects real-world conditions where fire sweeps across the ground surface. This differs from Goudie *et al.* (1992) and Allison and Goudie (1994), where samples were placed in the furnace on a flat surface. Alternatives to fine sand were considered, such as other pieces of identical rock, but the crack between a specimen and its immediate surroundings would have been a significant influence relative to test piece size. Fine sand is likely to be the most effective method for recreating the diffusion pattern of thermal energy within a larger area of exposed rock. Samples were placed in the furnace for 5 min at 500°C, moved to the environmental chamber, left to return to ambient conditions, removed from the sand, weighed, and modulus of elasticity measured. The procedure was repeated seven times.

RESULTS AND DISCUSSION

Simulation at 500°C following the standard procedure gives results which corroborate previous work (Table I). A comparison of the data from this study with the results of previously reported experiments confirms three points (Figure 1). First, a number of the rock types show significant change over seven cycles, with Serpentinite and Gabbro displaying a >20 per cent decrease in modulus of elasticity after only one simulation cycle. Second, some of the rocks, Chalk for example, change little at 500°C. Similar results arose in previous studies and it was suggested that higher temperatures are required for the threshold to be crossed

Table I. Percentage change in modulus of elasticity (decrease unless otherwise stated) at 500°C for the rock types used in this study

	Number of cycles						
Rock type	1	2	3	4	5	6	7
Serpentinite	25·34	37·49	48·9	53·3	40·63	45·54	50·7
Gabbro	23·6	23·6	33·98	35·83	30·37	29·57	34·97
Wehrlite	12·41	15·53	23·65	25·7	18·28	28·44	27·88
Chalk	2·71	2·71	6·74	8·52	5·57	6·67	4·35
Dolerite (feldspar rich)	2·17	+0·71	0·71	1·07	0·0	+1·11	+1·81
Dolerite (quartz rich)	+0·65	+2·59	+3·29	+3·58	+10·18	+3·5	+3·5

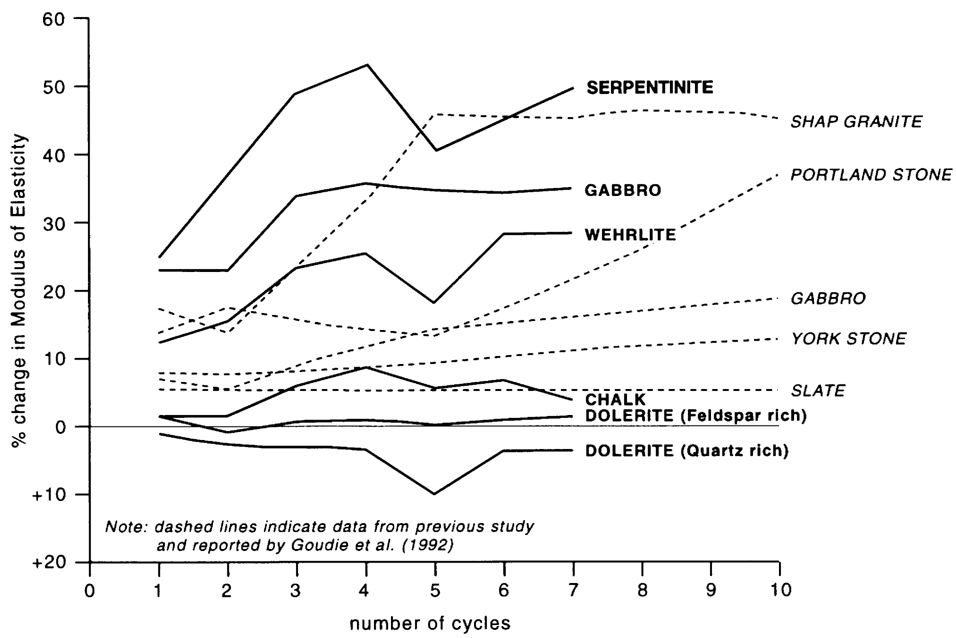

Figure 1. Comparison of the percentage change in modulus of elasticity for this study with the results of previous work

where material properties such as modulus of elasticity show significant change. Third, there is further evidence to support the case-hardening argument presented by Allison and Goudie (1994). Both of the Dolerites display an increase in modulus of elasticity. What has remained unclear up to this point is how temperature causes case-hardening and why it occurs in some of the rock types but not others.

The results of tests designed to simulate rainfall are presented in Table II and Figure 2. As expected, the change in modulus of elasticity is greater for Serpentinite, Gabbro and Wehrlite than recorded for the standard test. The Dolerites continue to show little change. Although one of the two materials does show a slight decrease in modulus of elasticity, it is not significant.

The results of tests where specimens were surrounded on all but one side in fine sand are presented in Table III and Figure 3. There are two noticeable trends which emerge from this part of the study. The first is that where modulus of elasticity decreases, the percentage change is much reduced. After one cycle the drop is less than 10 per cent for the Serpentinite, Gabbro and Wehrlite. The decrease remains below 10 percent for the latter two materials and only just rises above 16 per cent for the former. The implication is that while fire does have an effect on the material properties of some rock types, the time and number of fire cycles required for significant change to occur goes up. Results for the rock types where modulus of elasticity increases with

Table II. Percentage change in modulus of elasticity (decrease unless otherwise stated) at 500°C for tests designed to simulate rainfall and comparison with the results from standard tests

Rock type	Test details*	Number of cycles 1	2	3	4	5	6	7
Serpentinite	Rain simulation	29·13	24·28	55·23	50·35	33·02	57·94	56·22
	Standard	25·34	37·49	48·9	53·3	40·63	45·54	50·7
	Difference	3·79	+13·21	6·33	+2·95	+7·61	12·4	5·52
						Gross $\bar{x}$ % difference = 7·4		
Gabbro	Rain simulation	29·27	27·63	42·58	41·01	41·01	42·19	52·51
	Standard	23·6	23·6	33·98	35·83	30·37	29·57	34·97
	Difference	5·67	4·03	8·6	5·18	10·64	12·62	17·54
						Gross $\bar{x}$ % difference = 9·18		
Wehrlite	Rain simulation	20·94	21·84	35·05	35·05	31·78	38·05	42·69
	Standard	12·41	15·53	23·65	25·7	18·28	28·44	27·88
	Difference	8·63	6·31	11·4	9·35	13·5	9·61	14·81
						Gross $\bar{x}$ % difference = 10·52		
Chalk	Rain simulation	2·24	4·53	8·34	11·36	13·48	31·35	7·22
	Standard	2·71	2·71	6·74	8·52	5·57	6·67	4·35
	Difference	+0·47	1·82	1·6	2·84	7·91	24·68	2·87
						Gross $\bar{x}$ % difference = 6·03		
Dolerite (feldspar rich)	Rain simulation	3·78	1·02	3·42	2·39	2·04	0·43	0·78
	Standard	2·17	+0·71	0·71	1·07	0·0	+1·11	+1·81
	Difference	1·61	1·73	2·71	1·32	2·04	1·54	2·59
						Gross $\bar{x}$ % difference = 1·93		
Dolerite (quartz rich)	Rain simulation	1·21	+1·18	+0·58	+1·18	+1·18	+0·32	+0·93
	Standard	+0·65	+2·59	+3·29	+3·58	+10·18	+3·5	+3·5
	Difference	1·86	3·77	3·87	4·76	11·36	3·82	4·43
						Gross $\bar{x}$ % difference = 4·84		

* Rain simulation: tests with samples sprayed with H_2O on removal from furnace. Standard: tests following standard procedure and method of previous studies. Positive difference indicates standard test difference > rain simulation difference.

the number of simulation cycles show rather less change. Values remain small and largely insignificant, around 2 to 4 per cent for the Dolerites and 3 per cent for Chalk.

The data warrant a little more discussion, since the experiments were designed to reflect more closely real-world conditions. The sand clearly alters the heat diffusion characteristics of the test specimens. This ameliorating effect has to be recognized in the light of comments by Rice (1976), who considered differential volume changes within a rock upon heating. Volume increases will generate stresses within a rock mass which are likely to cause material disintegration, particularly where joints are widely spaced and unable to act as preferential lines of stress release. Parameters affecting the volume change can be quantified and used as a predictor of weathering processes such as spalling and other physical mechanisms which are likely to occur due to rapid temperature increases:

$$kx\left(\frac{a}{ke_{\mathrm{s}}}\right)1/(ks_{\mathrm{s}}/ae) \tag{1}$$

where k = thermal diffusivity, a = coefficient of thermal expansion, x = characteristic dimension, s_{s} = tensile strength, and e = modulus of elasticity.

A number of studies confirm the importance of the elements noted in Equation 1. Mirkovich (1978), for example, established an inverse relationship between thermal diffusivity and temperature, showing that a rock with a low thermal diffusivity has an increased likelihood of rupture. Winkler (1975) considered the

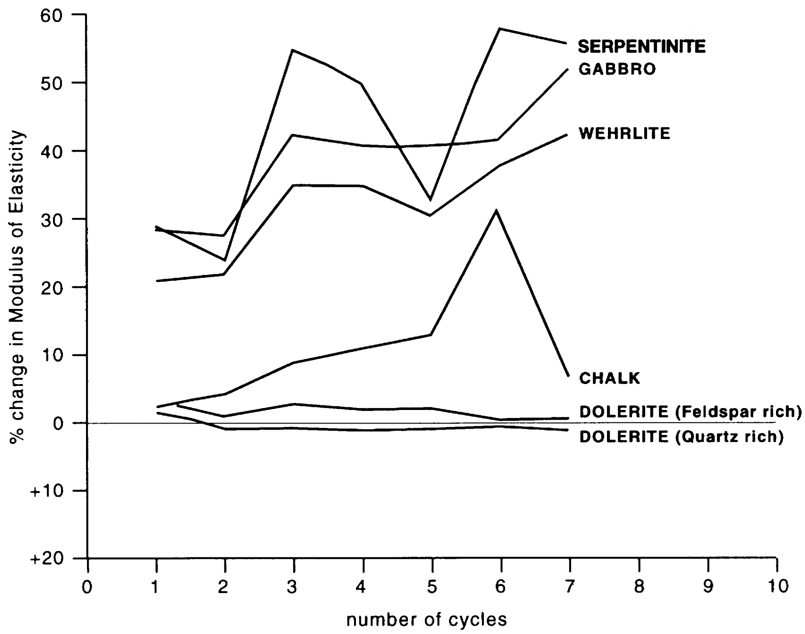

Figure 2. Percentage change in modulus of elasticity at 500°C for tests designed to simulate precipitation events

Table III. Percentage change in modulus of elasticity (decrease unless otherwise stated) at 500°C for tests designed to simulate the exposure of a single rock face to a passing fire and comparison with the results from standard tests

		Number of cycles						
Rock type	Test details*	1	2	3	4	5	6	7
Serpentinite	Single face	8·55	10·38	14·16	14·16	11·32	14·62	16·59
	Standard	25·34	37·49	48·9	53·3	40·63	45·54	50·7
	Difference	16·79	27·11	34·74	39·14	29·31	30·92	34·11
						Gross $\bar{x}$ % difference = 30·3		
Gabbro	Single face	5·38	7·69	8·86	10·0	10·0	8·71	11·12
	Standard	23·6	23·6	33·98	35·83	30·37	29·57	34·97
	Difference	18·22	15·91	25·12	25·83	20·37	20·86	23·85
						Gross $\bar{x}$ % difference = 21·45		
Wehrlite	Single face	3·59	4·21	4·21	6·45	8·04	6·41	9·0
	Standard	12·41	15·53	23·65	25·7	18·28	28·44	27·88
	Difference	8·82	11·32	19·44	19·25	10·24	22·03	18·88
						Gross $\bar{x}$ % difference = 15·71		
Chalk	Single face	0	+1·27	+1·27	+1·85	+1·85	+3·01	+3·57
	Standard	2·71	2·71	6·74	8·52	5·57	6·67	4·35
	Difference	2·71	3·98	8·01	10·37	7·42	9·68	7·92
						Gross $\bar{x}$ % difference = 7·16		
Dolerite (feldspar rich)	Single face	0	+0·6	+2·13	+1·82	+1·82	+4·82	+5·11
	Standard	2·17	+0·71	0·71	1·07	0·0	+1·11	+1·81
	Difference	2·17	+0·11	2·84	2·89	1·82	+3·82	+3·3
						Gross $\bar{x}$ % difference = 2·42		
Dolerite (quartz rich)	Single face	+0·53	+1·05	+1·41	+1·41	+2·63	+2·98	+2·98
	Standard	+0·65	+2·59	+3·29	+3·58	+10·18	+3·5	+3·5
	Difference	0·12	1·54	1·88	2·17	7·55	0·52	0·52
						Gross $\bar{x}$ % difference = 2·1		

* Single face: tests with sample embedded in sand and one exposed side. Standard: tests following standard procedure and method of previous studies. Positive difference indicates single face test difference > standard test difference.

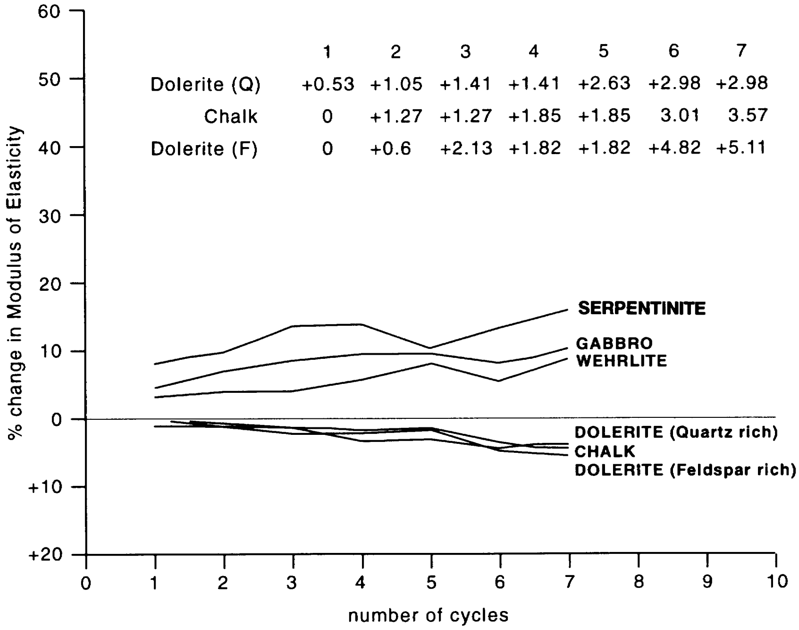

Figure 3. Percentage change in modulus of elasticity at 500°C for tests designed to simulate the exposure of a single rock face to a passing fire

characteristics of individual minerals comprising a rock type. At 530°C quartz increases in volume by 3 per cent and the volumetric expansion exerts a pressure of as much as 2500 atmospheres on surrounding mineral grains, making tensile strength and characteristic dimension important.

This being the case, there will be a threshold volume for any given rock where, for its geotechnical properties and thermal characteristics, physical disintegration under the influence of fire is likely to occur. Thermal stresses will be set up in the rock mass over a short period of time. It is the time element which, relative to the properties defined in Equation 1, results in a threshold being crossed and weathering occurring. An examination of material properties therefore provides a clearer explanation as to why some of the rocks used in this and previous studies display change and physical disintegration while others do not. More significant in geomorphological terms is the possibility that explanations of spatial variations in physical weathering in the natural environment may improve. This would require a knowledge of (a) the thermal behaviour of a rock, (b) its key geotechnical properties, and (c) climatic and other variables – such as fire – which will affect material behaviour, thereby permitting the formulation of more rigorous methods for establishing rock disintegration and sediment production. Work is presently in progress to this end.

The approach may also provide an explanation of increases in modulus of elasticity for some materials during laboratory simulation studies and what Allison and Goudie (1994) refer to as case-hardening. Although the heating of rock will expel free water, certain temperature thresholds have to be crossed relative to thermal diffusivity and coefficient of thermal expansion to release water locked within the mineral structure. The rock types in this study can be used by way of example. At 500°C the serpentine within Serpentinite and Wehrlite will be dehydrated of both its free and locked water. As the Serpentinite contains the greatest quantity of serpentine, the decrease in the modulus of elasticity is correspondingly large. The Gabbro contains actinolite, which at 500°C will undergo similar change and produce the dehydration products of amphibolites such as chlorite and water. The Dolerites, on the other hand, are meta-stable at 500°C and the temperature required to induce the dehydration of the water locked within the mineral structure will therefore be $>$ 500°C. The case-hardening effect in the Dolerites therefore is a product of the expulsion of free water but retention of locked water within the mineral matrix. Reduction in modulus of elasticity and

rock disintegration for Serpentinite and Wehrlite, on the other hand, is a function of the expulsion of both free water from void spaces within the rock and locked water from the mineral lattice.

CONCLUSIONS

Further tests have been undertaken to examine the effects of fire on rock weathering by laboratory simulation techniques. Two modifications to previous experimental designs have been made in an attempt to replicate more effectively natural environmental conditions. The test results corroborate previous studies but extend past work by providing more accurate indications of rock material property changes which can be used as indicators of disintegration and hence weathering. It appears that a combination of rock thermal properties, geotechnical characteristics and environmental parameters, such as temperature, can be used to quantify the likelihood of physical disintegration. The variables, in association with other details such as rock mineralogy, can be used to provide improved understanding of the case-hardening effect noted in this and in previous studies.

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